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High Temperature Dynamic Engine Seal Technology Development

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Combined cycle ramjet/scramjet engines being designed for advanced hypersonic vehicles, including the National Aerospace Plane (NASP), require innovative high temperature dynamic seals to seal the sliding interfaces of the articulating engine panels. New seals are required that will operate hot (1200-2000 °F), seal pressures ranging from 0-100 psi, remain flexible to accommodate significant sidewall distortions, and resist abrasion over the engine's operational life. This report reviews the recent high temperature durability screening assessments of a new braided rope seal concept, braided of emerging high temperature materials, that shows promise of meeting many of the seal demands of hypersonic engines. The paper presents durability data for: (a) the fundamental seal building-blocks—a range of candidate ceramic fiber tows; and for (b) braided rope seal subelements scrubbed under engine simulated sliding, temperature and preload conditions. Seal material/ architecture attributes and limitations are identified through the investigations performed. The paper summarizes the current seal technology development status and presents areas in which future work will be performed.

NASP ENGINE SEAL TECHNOLOGY DEVELOPMENT GWP #79 SCOPE

NASA Lewis Research Center is developing advanced seal concepts and sealing technology for advanced combined cycle ramjet/scramjet engines being designed for the National Aerospace Plane (NASP). Technologies are being developed for both the engine dynamic panel-edge seals and for the static seals that seal the heat-exchanger to backup-structure joints. Static seals such as the V-ring seals are required to prevent the hot gases flowing on the hot side of the heat exchanger (HEX) panels from escaping behind the HEX panels. As the heat exchanger panels heat to operating temperature, they must expand and glide over the V-ring seals without jamming. In cooperation with Rocketdyne, NASA is evaluating seal material sliding performance under simulated loads, speeds and temperatures as will be discussed.

The primary focus of Government Work Package (GWP) 79 is to develop durable, low leakage panel-edge dynamic seals required to seal the sliding interfaces of the articulating engine panels, such as the nozzle panel shown in the figure. Furthermore this technology will support the design and material selection of the fuel injector strut seals that seal the perimeter of the fuel injectors that articulate in and out of the hot gas flow stream.

The goals established for the seal development program are to assess the durability and leakage performance characteristics of those engine seal concepts showing promise of meeting the challenges of the NASP engine environment and to develop the critical seal technology data base to support the engine seal downselect process for transition from conceptual to preliminary engine design.

The objectives of this paper are to summarize the recent high temperature sealing technology accomplishments in the areas of seal concept development, seal material assessments, and braided rope seal subelement assessments, and to illustrate areas in which future work will be performed.

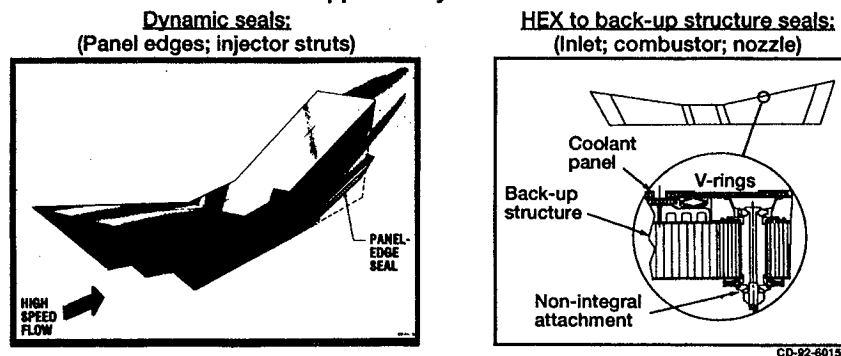
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NASP Engine Seal Technology Development (U) GWP #79 Scope

Objectives:

- Assess durability and leakage performance characteristics of engine seal concepts showing promise of meeting the challenges of the NASP engine environment
- Develop seal technology data base to support engine seal downselect process for transition to phase III

Engine Seal Locations Supported by GWP #79



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DYNAMIC SEAL OPERATING CONDITIONS

The goal of the dynamic seals is to prevent hot engine flow path gases, flowing over the engine panels (see previous figure), from escaping through the seal systems and damaging engine panel support and articulation systems. Seals are required that can prevent leakage of engine flowpath gases pressurized to 100 psi and flowing at temperatures in excess of air-hydrogen combustion temperature ($>4400^{\circ}\text{F}$) with minimal coolant (ref. 1). Complicating the sealing challenge further is the need for the panel-edge seals to seal against severely distorted engine sidewalls. The high chamber pressures and heating rates cause the weight-minimized engine sidewalls to deflect in some cases as much as 0.15 in., bowing the engine panels into compound curvature or spherical-like shapes. In order to minimize leakage the panel-edge seals must be sufficiently preloaded and compliant to seal against these engine wall curvatures.

The seals must be durable to resist wear and abrasion over the full mission life with an acceptable change in flow over the anticipated seal sliding distance. Seal materials must be selected to resist the high temperature oxidizing environment in the inlet and the hydrogen-reducing and steam environment in the combustion and nozzle sections respectively. During scramjet operation the engine core flows will be supersonic requiring that the seals resist the potentially erosive supersonic flow fields. Coupled with their cooling system the seals must survive intense ($>1200\text{ Btu/sq ft sec}$) rocket-level heating rates and the sudden thermal transient associated with engine startup and transition.

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Dynamic Seal Operating Conditions (U)

Operation:

- | | |
|--------------------------------|--|
| • Seal pressure differentials | 0-100 psi |
| • Operate hot | R.T. - up to 2000°F |
| • Seal large gaps | 0.03 - 0.15" |
| • Accommodate wall distortions | 0.15" in 18" span |
| • Meet target flow param. goal | $0.0005\text{ lb(He)}^{\circ}\text{R}^{1/2}/\text{sec/psi/ft of seal}$ |
| • Sliding velocity | 1 in/s |
| • Crush load | Limited by unpressurized heat exchanger limits |
| • Adjacent wall surface finish | $\geq 32\mu\text{in}$ |

Resist:

- Abrasion and wear for full mission life with acceptable change in flow over engine sliding distance
- Degradation by hydrogen, oxygen, steam environment
- Erosive supersonic flow field
- Rocket-level heating rates and sudden thermal shocks
- Unstart loads

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SEAL CONCEPTS UNDER DEVELOPMENT

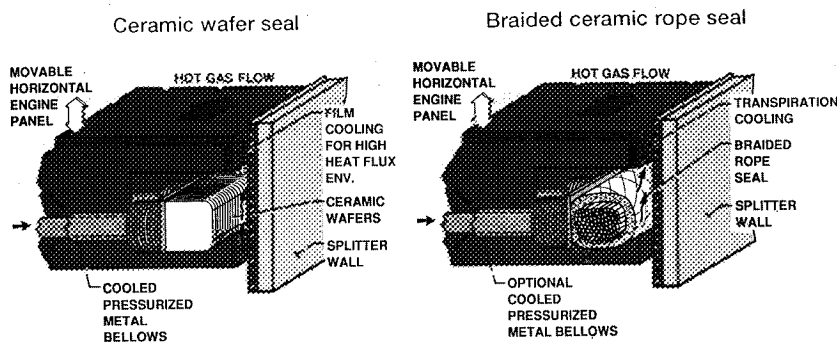
Two seal designs that show promise of meeting the demanding operating conditions of the NASP engine environment and sealing the gaps between the movable horizontal panels and the vertical splitter walls are the ceramic wafer seal and the braided ceramic rope seal. The ceramic wafer seal developed by NASA Lewis Research Center (ref. 1) is constructed of multiple ceramic wafers (capable of 2000 °F) mounted in a close tolerance horizontal channel along the side of the movable horizontal engine panel. The seal is preloaded against the engine splitter wall using an active preload approach such as a series of cooled pressurized metal bellows shown in the figure. The bellows push against a flexible metal backing plate that distributes the load to the wafers between the discrete circular bellows. The wafer seal conforms to expected engine splitter wall distortions by relative sliding between adjacent wafers. Leakage tests conducted at room- and high-temperatures (up to 1350 °F) at NASA Lewis Research Center have shown this design accommodates and seals both straight and simulated distorted walls meeting an industry established leakage limit (ref. 2).

The braided ceramic rope seal is fabricated using either two- or three-dimensional braid architectures. Braiding the seal from alumina-boria-silica or alumina-silica fibers allows the seal to operate up to 2000 °F. Several seal constructions based on braided rope seal technology are being considered for the engine depending on engine location and local heating rates. For the highest heating rate areas of the engine hollow braided rope seals pressurized from within are being considered. Using this approach the gas pressurization both inflates the seal conforming it to the expected engine wall deflections and transpires through the seal to effectively cool it. In less severe heating locations and injector strut locations solid rope seals are being considered. These seals can be either mounted in close conforming seal channels or if required, can be preloaded with an active preload system such as the metal bellows shown.

Solid braided ceramic rope seals having a high degree of uniaxial (0°) core fibers over-braided with several layers of sheath were tested under engine simulated temperature (up to 1350 °F) and pressure conditions (over 70 psi) at NASA Lewis (ref. 3). The rope seal leakage rates were higher than the wafer seal leakage rates. At an air pressure differential of 40 psi the braided rope seal leakage rates were nine times higher than the wafer seal at room temperature. Under the same pressure conditions but at a higher temperature of 1330 °F the rope seal leakage dropped significantly and was about twice the wafer seal leakage. Rope seal leakage rates met an earlier tentative leakage limit of 0.004 lb/s-ft for air pressure differentials up to 60 psi at 1330 °F. This good high temperature leakage performance combined with the rope seal's excellent conformability warranted further development of the seal concept. Areas where further development are required include architecture refinements to: (1) reduce seal permeability; and (2) to ensure seal survivability during dynamic operation. Results of a program to screen the durability performance of a range of braided rope seal architecture/material combinations are presented in this paper.

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Seal Concepts Under Development (U)



BRAIDED ROPE SEAL MATERIAL DURABILITY STUDIES

With recent interest in ceramic-matrix composites for high temperature aerospace applications (ref. 4), numerous high temperature ceramic fibers are emerging from various manufacturers. Prior to expensive seal and seal subelement scale-up, NASA initiated a program to assess the relative sliding durability of six candidate seal fiber materials and downselect amongst the fibers on the basis of: durability; chemical stability; and handleability/braidability (ref. 5). Using a unique high-temperature pin-on-disk tribometer at Lewis and a modified ceramic-tow specimen holder, relative sliding durability of the selected fibers were assessed as a function of temperature (R.T., 930 °F, 1650 °F), and environment (air and H₂). Fiber bundles composed of nominally 6000 fiber-ends were wrapped around the tip of a modified pin. Sizing applied by the manufacturers was removed from the fibers by the recommended heat-cleaning procedures. This condition was the baseline or "as-received" condition. The fibers were held in contact with engine-simulated pressures of 50 psi against the face of a slowly rotating Inconel 718 disk. The disk rotated past the specimen at a sliding speed of 1 in./sec, which is representative of the seal's sliding velocity.

Average relative sliding durability for each of the six fibers are shown in the figure. The fiber compositions were as follows: Nextel 312 (62Al₂O₃-24SiO₂-14B₂O₃); Nextel 440 (70Al₂O₃-28SiO₂-2B₂O₃); Nextel 550 (73Al₂O₃-27SiO₂); Nextel 610 (Al₂O₃); HPZ (57Si-28N-10C-5O); Tyranno (50Si-30C-17O-3Ti). The reader is referred to ref. 5 for a detailed discussion of the results found. Only the general trends will be highlighted herein. Because the goal of these tests were to assess relative durability of the various fiber candidates, the bars in the figure should be considered as a "barometer" of the fiber's performance. The longer and the more consistent are the bar's lengths the better the fiber's sliding performance is considered.

Heat treatment of the Nextel 312 and 440 fibers are recommended by the manufacturer to improve the fiber's resistance to attack in steam environments. The tow durability tests indicated a deleterious effect of this 950 °C 12 hr pre-exposure (denoted HT) on the materials' sliding durability at high temperature (see ref. 5 for discussion). Nextel 550 did not exhibit this drop-off in fiber sliding durability after the same pre-exposure, as shown in the graph. This observation combined with a relatively high sliding durability warranted further investigation with this experimental fiber from 3M.

Tyranno exhibited significant oxidation at temperature. Nextel 610 exhibited poor handleability performance due to its high modulus. Based on these grounds these fibers were not pursued any further. HPZ exhibited very uniform sliding durability over the full temperature range and was tested further in hydrogen environments.

Braided Rope Seal Material Durability Studies (U)

Objective:

Assess relative sliding durability of seal fiber materials & downselect

Approach:

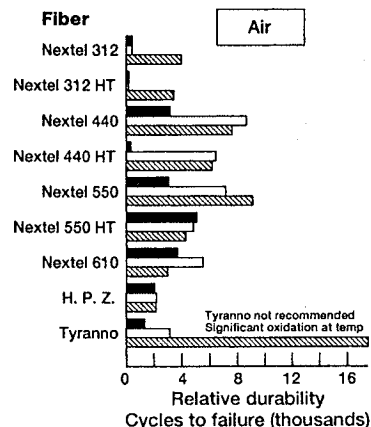
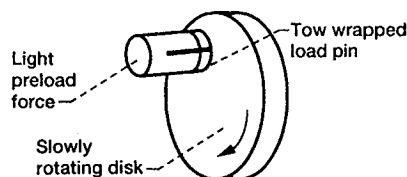
Determine cycles-to-failure of competing ceramic fibers under engine simulated:

- Temperatures
- Air; H₂ environments
- Speeds & surface conditions

Schedule:

Material durability (Air) Comp. 3rd Q CY91
Material durability (H₂) 1st Q CY92

Apparatus



Nextel 550; HPZ; & Nextel 440 (as rec'd.) exhibited best balance of:

- Sliding durability (Air);
- Air stability;
- Handleability

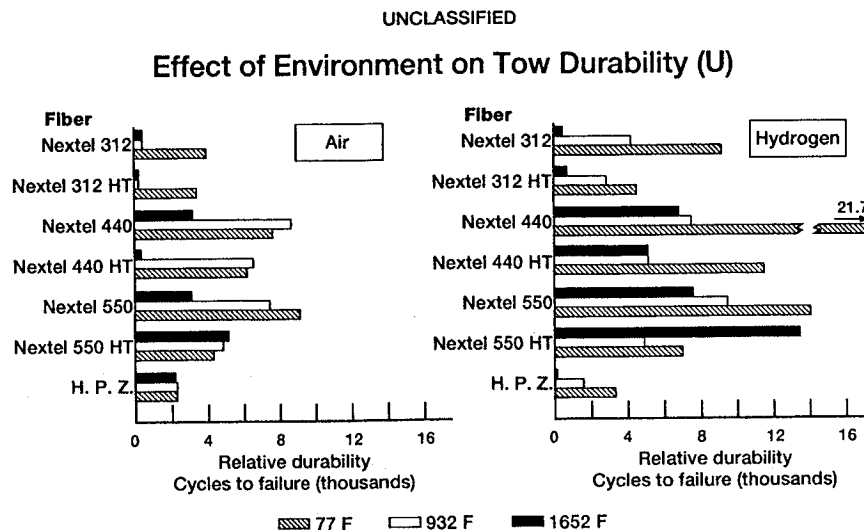
EFFECT OF ENVIRONMENT ON TOW DURABILITY

Fast burning, high specific impulse hydrogen is the fuel of choice for the NASP's ramjet/scramjet engines. To assess the effects of a reducing hydrogen environment on the ceramic fiber sliding durability, tow durability tests (ref. 6) similar to those described for air were run in a hydrogen-purged pin-on-disk tribometer at NASA Lewis. The results of these tests in ambient pressure hydrogen are shown here as a function of temperature where the tow specimen design, loads, speeds and counterface material were the same as before. Relative durability of the same fibers run in air are also shown for comparison purposes.

An encouraging result observed in these test was that the high temperature sliding durability of the oxide ceramics was better in hydrogen than in air. Although a minor reduction in relative fiber sliding durability was observed for Nextel 312 and 440 fibers that were heat treated (denoted HT), the reduction was not as severe here as was in the air environment. The average fiber durability of Nextel 550 was slightly better than the other oxide ceramic fibers at elevated temperatures. The high temperature sliding performance of the HPZ fiber material was dramatically worse in the reducing environment than it was in air indicating limitations of this fiber in hydrogen environments (ref. 6).

Based on these investigations, the high temperature air environment appears to be the discriminating condition (i.e., air versus hydrogen) under which near-term seal subelement durability tests need to be run to select the best material/architecture combinations. This is an encouraging result considering the expense of performing seal flow and durability tests with hot hydrogen.

It is noted however for the tests performed herein, time at temperature in the hydrogen environment was generally limited to less than 2 hr (equivalent to approximately 6 engine missions). Further tests will be required to assess fiber performance for the 150 mission engine life (≈ 55 hr) exposure to hot hydrogen. The effects of 55 hr, 2000 °F hydrogen exposure on seal fiber tensile strength and weight loss will be assessed by Rocketdyne. Tests must also be performed to assess the effects of engine-simulated steam environments on fiber performance.



Observations:

- At temperature, oxide ceramics exhibit better sliding durability in H₂
- Nextel 550 durability not degraded by hot pre-exposure or by hydrogen

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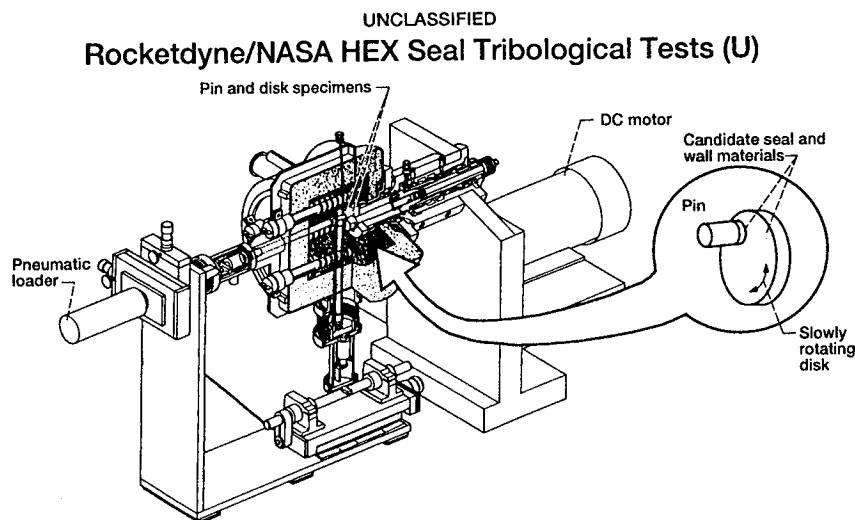
ROCKETDYNE/NASA HEX SEAL TRIBOLOGICAL TESTS

Metal "V"-ring or "U"-ring seals are being designed to seal the heat exchanger panels to the nonintegral backup structure. Nonintegral heat exchanger panels line the wetted surfaces of the NASP engine and expand while coming up to operating temperature. The heat exchanger panels must easily glide over these thin-gage flexible seals without causing damage to either the seal or heat exchanger panels. Seals coated with compliant low friction coatings are being designed to accomplish this task.

On account of the numerous combinations of seal, heat exchanger and coating materials being considered for the engine, a simple cost-effective method was required to assess the seal materials' tribological performance. Different materials and coating systems are being considered for each of the engine inlet, combustor and nozzle sections. Rocketdyne and NASA Lewis will cooperatively assess the friction and wear of many of these material combinations using NASA Lewis' pin-on-disk tribometer, shown in the figure.

Pins fabricated of representative seal materials (i.e., HS188 and Incoloy 909, etc.) will be slid against the face of an oscillating disk made of heat exchanger wall materials (i.e., NARLOY Z, HS188, Incoloy 909, etc.), coated with representative oxidation coatings where required.

Benefits of solid film lubricants such as gold and nickel will also be evaluated. Tests will be run under simulated sliding and stress conditions at temperatures up to 1550 °F in either air or hydrogen environments.



Objective:

Assess wear and friction coefficients of heat exchanger seal (coated/uncoated) and engine wall material pairs at temperature using NASA LeRC tribometer

Schedule:

Complete assessments 2nd Q CY92

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LINEAR SEAL HOT WEAR SCREENING

A cooperative program between NASA, Pratt & Whitney and Drexel University was initiated to rank the relative durability of candidate braided rope seal architecture/material combinations. In this program representative 0.5-in. diameter solid rope seals were fabricated, leak tested, scrubbed under engine simulated conditions, and subsequently leak tested after scrubbing. Seal scrubbing tests at temperature (1300 °F) have been completed. Room temperature tests are underway.

The seals were scrubbed using the fixture shown in the photo. Seals were mounted in rectangular groove channels in facing seal holders and scrubbed against the sides of the vertically articulating Inconel 600 saber. Preload was applied to the backsides of the seals through crush bars that maintained the seals in intimate contact with the sabers. A seal preload of 20 psi (40 lb load over a 4- by 0.5-in. contact area) was applied through calibrated load bars. Seal drag or friction was measured through a calibrated load cell in the articulating saber load-path. Average friction coefficients were evaluated by dividing one-half of the measured drag load by the applied 40 lb normal load. The gap between the articulating saber and each seal holder was 0.035 in. Rope seals denoted M1-M4a,b, and M6 were braided using two-dimensional braid architectures. Two-dimensional braided seal architectures have relatively low leakage characteristics (ref. 3) and low-cost fabrication. Seals M1 and M2 are hybrid seals developed by NASA Lewis that combine the durability characteristics of a ductile, fine-wire metal sheath braided over a high-density low-permeability uniaxial core made of fine (8 μ m Nextel 440) ceramic fibers. To assess the effect of braid angle on seal durability and leakage, seals M1 and M2 were braided using a high braid angle (80°) and a medium braid angle (40°). Immediate availability of fine wire diameters and materials limited wire selection for these tests to 0.004 in. Inconel 600 wire. As will be shown, these are design parameters that need to be optimized for the final engine application. Seal M3, an all-metal version of M1, was not tested on account of its heavy weight and because of limited test-stand time. For reference purposes, a detailed description of the seal construction parameters are listed in Table I at the end of this report.

Seals M4a and M4b were virtually identical seal architectures differing mainly by their materials, Nextel 440 and Nextel 312, respectively. Both seals had a high percentage of uniaxial core fibers (M4a: 66% and M4b: 69%) over-braided with six layers of sheath at a braid angle of 80°. Studies (ref. 3) have shown the benefit of small filament diameter on leakage. Therefore, these seals were made of the smallest (8 μ m) commercially available Nextel fibers. Seal M5 was fabricated of Nextel 440 using a high percentage (70%) uniaxial core. This seal was over-braided using a three-dimensional braided sheath that incorporated longitudinal (axial) stuffers to help "pin" the braid architecture. Seal M6 was fabricated using Nextel 550 with a 87% uniaxial core and two layers of braided 55° sheath. Seal M6 was braided using the smallest (12 μ m) commercially available Nextel 550 fibers.

Linear Seal Hot Wear Screening (U)

Objective:

Rank relative durability of candidate braid seal architecture/material combinations

Approach:

Fabricate/scrub seal specimens to assess durability dependence on:

- + Braid architecture
- + Material and material conditioning
- + Temperature

Schedule:

Rank relative durability 2nd Q CY92

Hot screening rig:



No.	Seal construction
1	Hybrid: Metal sheath (Hi braid ang) ceramic core
2	Hybrid: Metal sheath (Med braid ang) ceramic core
3	All metal: Sheath (Hi braid ang)/core
4a, b	All ceramic: Sheath (Hi braid ang)/core a) Nextel 440; b) Nextel 312 Heat treated & As received conditions
5	All ceramic: 3-D Sheath (Hi braid ang) Uniaxial core
6	All ceramic: Sheath (Hi braid ang)/core Nextel 550

SOLID SEAL DURABILITY SCREENING TESTS
NEXTEL 440 - ROOM TEMPERATURE

Room temperature scrubbing tests were recently completed on a pair of seals denoted M4a. This seal was braided of small filament diameter ($8\text{ }\mu\text{m}$) Nextel 440 fibers to take advantage of their low permeability. These seal specimens were first heat cleaned ($593\text{ }^{\circ}\text{C}$; $1100\text{ }^{\circ}\text{F}$ for 1-1/2 hr) and then heat treated prior to test using the manufacturer's recommended pre-exposure to $950\text{ }^{\circ}\text{C}$ ($1740\text{ }^{\circ}\text{F}$) for 12 hr to stabilize the fiber microstructure against degradation by steam environments. This was the conditioning followed for the all-ceramic seals M4a, M4b, M5 and M6 to be run in room temperature where it is convenient to periodically inspect the sheath damage at discrete cycle intervals. Shown in the figure are the seal surfaces rubbed against the Inconel saber.

Except for minor sheath damage on the front of the right seal, both seals survived the simulated duty-cycle mission (2000 cycles at 2 in./cycle). For the purposes of these tests seal survival was defined as completing the simulated scrubbing duty cycle without: (a) breaking through multiple layers of the sheath; and (b) exhibiting erratic friction behavior (i.e., friction spiking $\mu \geq 1$).

Seals M4b (heat treated) made to the identical architecture as M4a but braided instead of Nextel 312 fibers exhibited considerably poorer performance than exhibited here. During room-temperature test setup and measurement of the lateral loads required to move the seals in the holders, considerable damage was done to the outer sheath layers prior to any cycling against the saber. These seals tests were terminated.

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Solid Seal Durability Screening Tests (U)

Result: 2-D Braid, All-ceramic seal successfully completes 2000 cycles
at room temperature

Left seal:



Right seal:



Conditions:

Seal architecture: M4a-2D(42%)-NX440(700/8)-3144/66% Core
-NX440(700/8)-24x6/2/80° Sheath
Seal gap: 0.035 in
Preload: 40 lb over 4 in
Friction coefficient: 0.8-0.9

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SOLID SEAL DURABILITY SCREENING TESTS NEXTEL 440 - HIGH TEMPERATURE

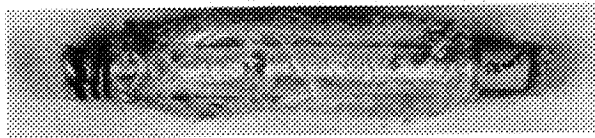
High temperature scrubbing tests have been completed for all of the seal architectures. Shown in this figure is the result of scrubbing another pair of seals denoted M4a. These seals were braided of Nextel 440 and taken from the same braiding-run as the room temperature seals. The seals were heat cleaned to remove the manufacturer's sizing. The seals were not heat treated because of the deleterious effects on material high-temperature durability shown previously in the tow durability tests. The seal performed poorly in these scrubbing tests. Nearly all of the sheath layers were broken through in only 20% of the simulated duty cycle. During tests multiple pieces of seal fiber material were observed falling off of each of the seal specimens. Tests were halted after noticing considerable wear debris accumulated on the floor of the furnace and on account of erratic measured friction behavior.

Several observations can be made comparing the results of these room and high temperature durability tests using identical architecture seals. As demonstrated by the seal subelement tests, and supported by the tow durability tests, material durability is considerably worse at high temperature than at room temperature demonstrating the need to qualify all NASP engine seals at engine simulated temperatures. Also it is clear that methods of strengthening the seal's sheath are required to enable the seals to survive the NASP engine's punishing environment.

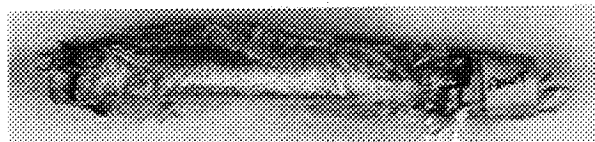
Solid Seal Durability Screening Tests (U)

Result: 2-D Braid, All-ceramic seal sheath nearly worn through after 420 cycles at 1300 °F

Left seal:



Right seal:



Conditions:

Seal architecture: M4a-2D(42%)-NX440(700/8)-3144/66% Core
-NX440(700/8)-24x6/2/80° Sheath

Seal gap: 0.035 in.
Preload: 40 lb over 4 in.
Friction coefficient: 0.86

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SOLID SEAL DURABILITY SCREENING TESTS HYBRID SEAL - HIGH TEMPERATURE

The hybrid braided rope seal with its durable metal sheath braided over the light-weight, dense ceramic core has demonstrated a new level of seal durability at temperature. The seals shown here survived the full 2000 cycle simulated seal duty-cycle at 1300 °F with no fiber breakage. Appearance wise the only indication that the seals were run were minor polishing of some of the metal filaments in the rub zone. Other measures of the hybrid seal's excellent performance including minimal change in weight and low friction will be shown in subsequent sections of this report.

The dark appearance is the metal oxide formed during pre-oxidation heat cleaning. The cycle time at temperature is not long enough to grow a stable oxide on the metal wires. Therefore prior to flow testing and scrubbing the seals were preoxidized at 593 °C (1100 °F) for 1-1/2 hr. Uniform friction and sliding performance was observed throughout the high temperature tests.

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Solid Seal Durability Screening Tests (U)

Result: Hybrid seal successfully completes 2000 cycles at 1300 °F
Hybrid: Metal fiber sheath over ceramic fiber core

Left seal:



Right seal:



Conditions:

Seal architecture: M1-2D(42%)-NX440(700/8)-3166/94% Core
-IN600(569/100)-24x1/5/80° Sheath

Seal gap: 0.035 in.

Preload: 40 lb over 4 in.

Friction coefficient: 0.35

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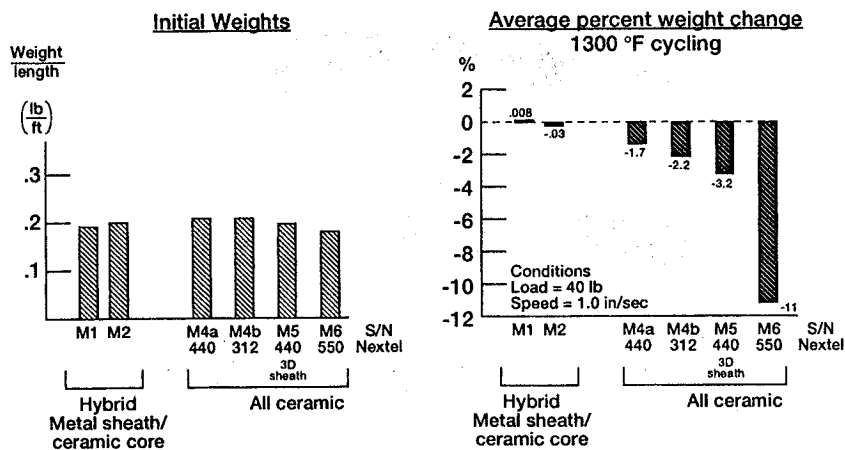
COMPARISON OF SOLID SEAL WEIGHTS

Low-weight engine components are required to enable the NASP to successfully reach orbital speeds. The weights of each of the seals were measured before and after the seal scrubbing tests. The initial seal weights are shown in the left figure. The weights shown were calculated from the average seal weight divided by the seal's length in feet. All seals tested were 5.6 in. long and nominally 0.5-in. diameter providing a uniform basis to compare various seal-design weights. As shown in the figure, the seal weights fall in a narrow range of 0.19-0.21 lb/ft.

The average (e.g., left and right) percentage change in the seal weight after cycling at 1300 °F is shown in the right figure. The change-in-weight of dynamic seals is one method of comparing relative seal durability. The hybrid seal percentage weight change is almost negligible at 0.03%. The average percentage change in weight for seals M4a, M4b, and M5 were between 1.7 and 3.2% and occurred over limited cycling as will be shown later. The average percentage weight change of the M6 seals made of Nextel 550 was higher and was 11%. A potential explanation for this higher percentage weight change may be the slightly different sheath braid construction. To preserve the same sheath thickness (i.e., for flow considerations) of M6 versus M4a and M4b with the larger 2000 denier commercially available Nextel 550 tows, two sheath layers were used instead of six. The fewer layers resulted in a more rapid or abrupt change in sheath-to-core wear. As a result, the saber removed a limited number of uniaxial core fibers just prior to shut down. Though more weight loss was observed, a considerably higher fraction of the seal duty cycle was completed as will be discussed later in the paper.

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Comparison of Solid Seal Weights (U)



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COMPARISON OF SOLID SEAL LEAKAGE RATES

Room temperature leakage rates were measured for each of the seals before and after the high temperature (1300 °F) scrubbing using a specially designed test fixture. In this fixture the last 0.8-in. lengths of the seal ends are "buried" in the ends of the test fixture with only the center 4 in. of seal exposed to air or helium. This approach virtually eliminates the end leakage problem common in linear seals testing. The seal is preloaded from behind using an inflatable bladder that applies a uniform preload to the seal contact zone. A significant leakage data base has been generated for various applied pressure differentials and representative preloads.

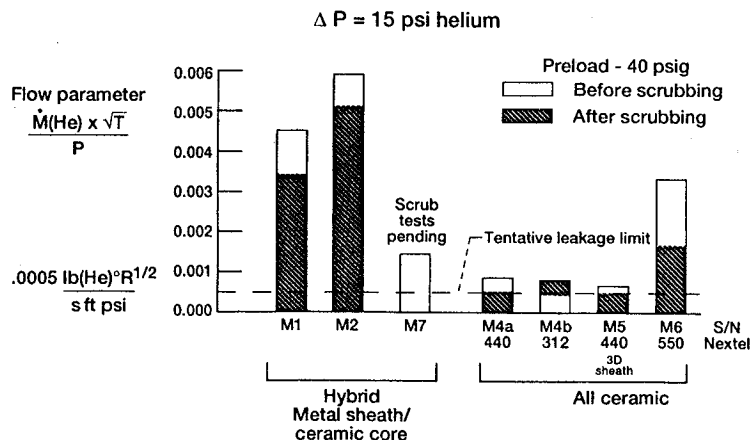
In this figure, helium leakage rates per foot-of-seal-length are plotted in terms of "flow parameter" borrowed from turbine-engine film-cooling investigations. The pressure drop across the seal is 15 psi, resulting in a normalizing pressure of 29.7 psi. Seal preload for these tests was 40 psi. Pre- and post-scrubbing leakage rates are shown in the open and shaded bars, respectively. For the all-ceramic seals where considerable sheath damage was accumulated, the seal had to be carefully installed in the leakage test fixture.

Generally the seal leakage rates after scrubbing were less than those prior to scrubbing. This result is believed to be caused by compaction of the seal fibers during the scrubbing cycling. The all-ceramic designs (M4a, M4b and M5) with the small diameter fibers had the lowest leakage rates, essentially meeting the tentative leakage limit for this pressure differential. Seal M4b post-scrubbing leakage rates were higher than pre-scrubbing leakage rate on account of the difficulty testing these badly worn seals. The pre- and post-scrubbing leakage rates of the M6 seal braided of the 12 μ m Nextel 550 fibers were above the tentative flow goal, for room temperature helium. Lower leakage rates would be possible from this basic architecture by using smaller filament (i.e., 8 μ m, Nextel 440) fibers for the uniaxial core. It is also noted that leakage rates at higher temperatures would be lower than the room temperature leakage rates measured herein, (ref. 3).

The hybrid seal post-scrubbing seal leakage rates were also less than the pre-scrubbing leakage rates. The high braid angle (80°) M1 seal had a leakage rate about one-third less than the medium braid angle (40°) M2 seal. However, both hybrid seal leakage rates were higher than the tentative flow goal, sealing room temperature helium. Clearly architecture refinements are required to reduce these leakage rates to acceptable levels.

Techniques that are being investigated to further reduce leakage flow while preserving the hybrid seal's durability include reducing wire diameters along with other advanced approaches explained later in this report. To shed some early light on the benefits of reducing filament diameters, another seal denoted M7 was braided using the same basic design as M1 but using 0.001 in. metal wires instead of 0.004 in. The leakage rates of this seal are also shown and are about one-third those of M1. The seal's pre-scrubbing leakage was just over the target flow goal. The effects of scrubbing on this seal's performance will be assessed in future tests.

Comparison of Solid Seal Leakage Rates (U)
Room Temperature Flow After 1300 °F Cycling

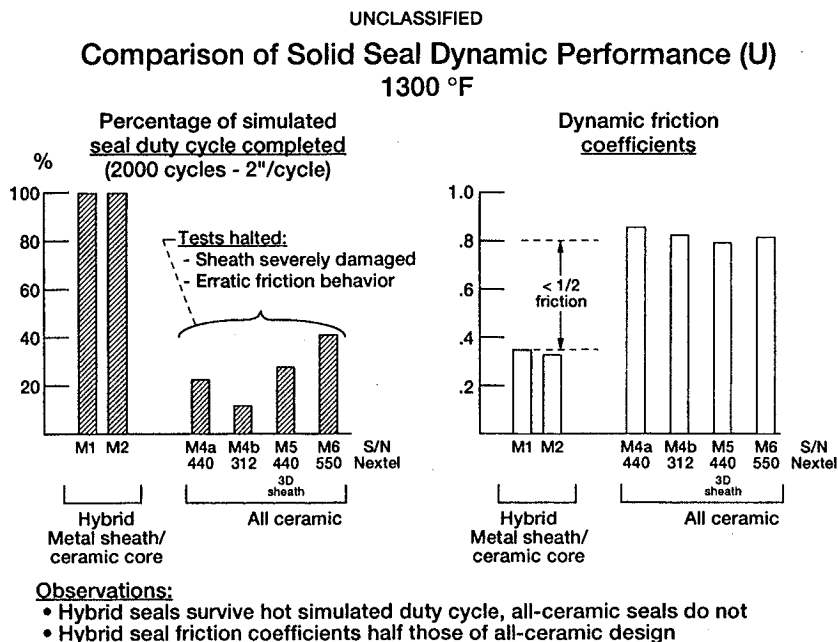


COMPARISON OF SOLID SEAL DYNAMIC PERFORMANCE

During the current conceptual engine design phase only preliminary estimates have been made for the total missionized seal sliding distance. Estimates of 4000-5000 in. have been given. For the purpose of these seal screening tests the simulated seal duty cycle of 4000 in. was selected. The percentage of the duty cycle completed by the seals is plotted in the figure on the left. The M1 and M2 hybrid seals completed the entire 2000 cycle duty-cycle with no fiber breakage. No scraping of the saber surface was observed during the tests.

The all-ceramic seal designs tested exhibited poor durability performance. Tests were halted when the sheath had been severely damaged (nearly worn through) and when erratic friction behavior ($\mu \geq 1$) was measured. M4b (Nextel 312) seal completed 14% and M4a (Nextel 440) completed 21% of the duty cycle. M5 (Nextel 440) with a three-dimensional braided sheath survived slightly longer completing 25% of the duty cycle. M6 (Nextel 550) survived the longest of the all-ceramic seals completing 42% of the duty cycle.

Seal friction is another issue that must be considered when performing the engine design. High friction between the articulating seals and the adjacent engine surfaces require relatively larger, heavier actuators to move the panels and optimize flow-path performance. High friction can also limit the engine controllability in the case of likely engine unstart/restart conditions. To re-establish engine inlet shock boundary conditions at hypersonic speeds, it is likely that engine panels may have to be slewed quickly. It is anticipated that low seal friction would aid engine controllability during transient conditions, and would allow somewhat smaller, lighter-weight engine actuators. As shown in the figure on the right, the hybrid seal friction coefficients were about 0.35—less than half the friction coefficients of the all-ceramic designs. This relatively low hybrid seal friction is believed a direct result of the lubricating effect of the stable metal oxides that form on the metal fibers.



HIGH TEMPERATURE DYNAMIC SEAL LEAKAGE FLOW CHANGE VERSUS CYCLES

NASA Lewis is developing a new high temperature dynamic seal rig to be used to assess the change in dynamic seal leakage flow versus simulated cycles to compare and downselect amongst several candidate engine seals. Unlike previous tests where flow and durability measurements were done in independent test fixtures, both parameters can be measured in the same test rig without disturbing the seals.

Seals will be mounted in facing seal holders and preloaded against an articulating saber inserted between the two seals as shown in the lower figure. Hot, metered air flow is supplied to the base of the seals at engine simulated temperatures up to 1500 °F and pressures up to 100 psi. A modular fixture design is employed so that different seal sizes and geometries can be tested in the future. The seal holders can be removed from the seal bases and replaced with other holders minimizing re-work and downtime. Different seal gap settings are tested by using different thickness sabers inserted between the seals. Gas temperatures, pressures and leakage rates will all be measured and logged using a new streamlined computer data acquisition system.

High Temperature Dynamic Seal Leakage Flow Change vs. Cycles (U)

Objective:

Assess change in dynamic seal leakage flow and downselect amongst competing dynamic seals

Approach:

Quantify change in seal leakage flow vs. cycles & assess dependence on:

- + Seal construction
- + Temperature and pressure
- + Wall condition

Schedule:

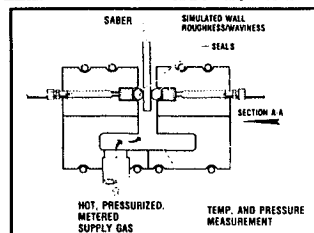
Begin tests

2nd Q CY92

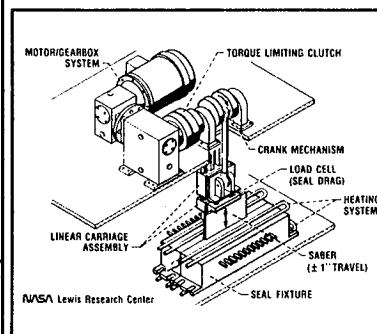
Durable/low leak seals

2nd Q CY93

Modular fixture for multiple seals



Hot dynamic seal rig:



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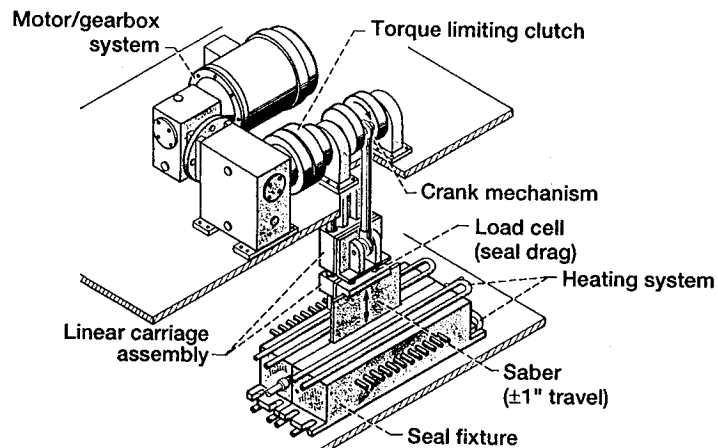
HIGH TEMPERATURE DYNAMIC SEAL RIG

Engine simulated sliding speeds ranging from 0.1 to over 1 in./sec will be used to assess the effects of sliding speed on seal durability. Preliminary estimates of the total seal sliding distance required for the mission range up to 5000 in. This sliding distance will be accumulated in 1250 cycles (4 in./cycle).

Seals will be scrubbed against the articulating saber which is nominally 12 in. wide. The saber is held in alignment relative to the seals and fixture through preloaded linear bearings that are precision aligned. Seal drag forces will be measured using load cells in series with the saber and articulation systems. Seal friction coefficients will be evaluated for each seal by dividing the measured friction force by the applied normal force.

Main rig heating will be performed with nickel-chrome heating elements bolted onto the test rig. To minimize heat loss and to speed heating, four inches of low conductivity insulation will be installed over the rig.

High Temperature Dynamic Seal Rig (U)



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HIGH TEMPERATURE DYNAMIC SEAL RIG PRELIMINARY TEST MATRIX

A preliminary test matrix of seals to be tested in the new dynamic rig is shown here. Four types of solid seals will be tested ranging from various braided rope seals to the ceramic wafer seal. Based on the excellent durability performance of the hybrid seal, this will be the leading seal tested in the fixture. Braiding the hybrid seal sheath of high temperature metal wires including HS188 amongst others will allow the seal to operate at temperatures in the range of 1700-2000 °F. HS188 has a more tenacious oxide layer important for low friction properties.

A co-braided seal concept developed by NASA Lewis will also be fabricated and tested to exploit the beneficial characteristics of the hybrid and the all-ceramic seals. In this seal, high-temperature durable metal filaments will be co-braided with small-diameter, low-permeability ceramic tows over a dense uniaxial ceramic core to synergistically reduce seal leakage rates while maintaining acceptable seal durability.

Two geometries of the ceramic wafer seal will be investigated. The 0.5-in. square wafer seal will be tested based on its demonstrated low leakage rates (ref. 2). The rectangular (0.5 by 1 in.) ceramic wafer seal will be tested to examine its improved piloting potential.

Also shown in the figure are the temperatures, pressures, and preloads that will be examined during the tests. Using the pressurized metal bellows one can actively preload the seal throughout the tests. To examine the ability of the solid rope seal to perform as a gland-packing, the seal will be installed in a fixed geometry gap. Change in flow versus wear cycles will be assessed for both of the above preload conditions.

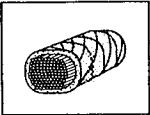

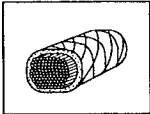
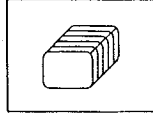
Varying the thickness of the saber one can assess the effect on seal leakage due to the change in seal gap. The effects of engine wall distortion on seal leakage will also be assessed by machining a simulated wave into the saber surfaces. The saber can also be coated to assess the beneficial effects of solid lubricants on seal durability and friction.

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High Temperature Dynamic Seal Rig (U)

Preliminary Test Matrix

Seal Concepts

	Hybrid Sheath: • HS188 • 2D-Hi braid angle Core: • Nextel 440 • Hi percentage uniaxial		Co-braided Sheath: • HS188/Nextel 550 co-braided sheath • 2D-Hi braid angle Core: • Nextel 440; 550 • Hi percentage uniaxial
	All-ceramic Sheath: • Nextel 550 • 2D-Hi braid angle Core: • Nextel 440; 550 • Hi percentage uniaxial		Ceramic wafer Size: 1/2" sq; 1/2"x1" rectangular Thick: 1/8" Mat'l: Al ₂ O ₃ ; Si ₃ N ₄

<u>Temperature</u>	RT, 500, 1000, 1500 °F		
<u>Pressure</u>	<u>Engine:</u> 0 - 100 psi	<u>Preload:</u> Active: 20, 40 psi Passive: Preload retention vs cycles	
<u>Wall condition</u>	Flat: 0.032", 0.075 gap;	Wavy: Simulate engine wall distortion	
	Solid lubricants: Au; Ag; Other candidate coatings		

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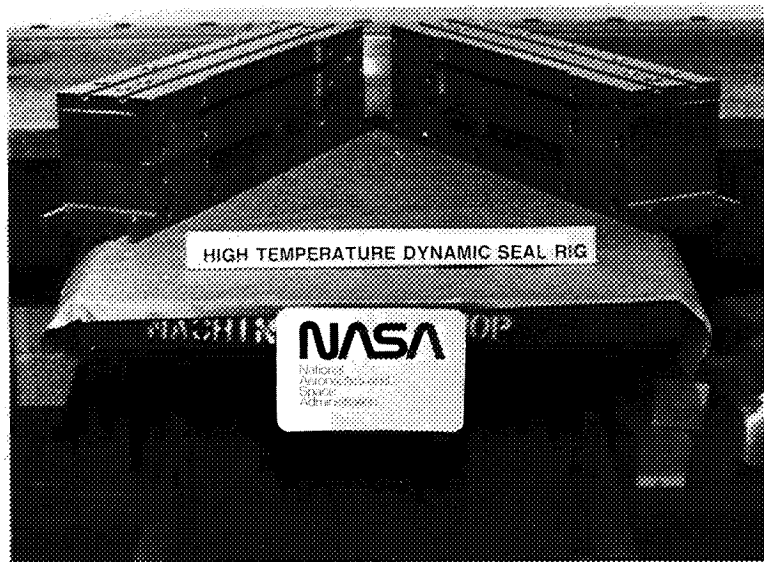
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FABRICATION OF HIGH TEMPERATURE DYNAMIC RIG COMPONENTS

Good progress has been made on the high temperature rig development. Rough machining of the Inconel X-750 fixture components has been completed, as is shown in this photo. Orders have been placed for all long-lead components and most commercial components have already been delivered. Site preparation is underway and rig safety reviews are in process. The current test schedule calls for beginning checkout tests in the second quarter of 1992.

Fabrication of Rig Components (U)



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SUMMARY

In support of the National Aerospace Plane program, NASA Lewis is developing high temperature engine seal concepts and the seal technology database to support program transition from conceptual to preliminary engine design. A strong program has been put in place to develop and select those engine seal concepts that have the best balance of durable/low leakage/high temperature performance. Elements of the program include concept development, fundamental material studies, seal subelement durability tests, and finally seal prototype leakage-qualification tests.

Alternate tow durability tests were run to assess the relative sliding durability of a range of candidate ceramic materials under both air and hydrogen environments. Tests were run at room temperature, 930 and 1650 °F. These tests demonstrated the deleterious effects on the high temperature sliding durability of Nextel 312 and 440 caused by heat treating the fibers at 950 °C for 12 hr. This heat treating or material conditioning is recommended by the manufacturer to improve fiber resistance to steam environments. Unfortunately, this pre-exposure temperature falls well within the intended seal operating temperature. The tow durability tests also revealed the encouraging result that a new fiber Nextel 550 ($\text{Al}_2\text{O}_3\text{-SiO}_2$), was not degraded by this temperature pre-exposure. A second sequence of tow durability tests with the same fibers were run in hydrogen at the same three temperatures. These tests showed that the oxide ceramic fibers exhibited somewhat better sliding durability in hydrogen than in air at temperature.

The relative sliding durability of a range of seal subelement architecture/material combinations were assessed in a joint program between NASA, P&W and Drexel University. The high temperature durability of five different braided rope seals have been assessed. Only the hybrid braided rope seals having a metal sheath braided over a dense uniaxial ceramic core survived the full 2000 cycle duty-cycle. Though the all-ceramic seals exhibited lower leakage rates than the hybrid seals, the all-ceramic seal sheaths were severely damaged after only 14-42% of the duty-cycle. Based on the results obtained, the hybrid architecture will be further optimized to exploit its excellent durability and low friction while reducing leakage flow rates.

A new high temperature dynamic seal test rig is being developed at NASA Lewis to assess the change in seal leakage versus wear cycles. The fixture will test seals at engine simulated temperatures up to 1500 °F, pressures up to 100 psi and sliding speeds up to 1 in./sec. This rig will serve the useful function of assessing those competing seal concepts having the best balance of high temperature durability and leakage flow resistance as the program progress from conceptual to preliminary design.

Recommendations:

Based on the collective findings of the tow durability tests and the seal subelement tests, the following recommendations for future solid-rope seal investigations are made:

1. The low high-temperature durability of the Nextel 312 fibers, combined with their sensitivity to moisture- and temperature-exposure, limit the use of these fibers to applications where severe abrasion will not be encountered.
2. To achieve the required durable low-leakage operation expected of the dynamic solid rope seals at temperature, new seal architectures and material combinations including those described herein must be pursued.

Summary (U)

- Programs to develop and select dynamic seals having the best combination of durable/low leakage/high temperature performance underway.
- Alternate tow durability tests assess high temperature relative sliding durability of a range of candidate ceramic fibers in air and hydrogen environments.
- Linear seal hot wear screening tests demonstrate excellent durability and low friction characteristics of new hybrid seal. Seal architecture to be optimized for acceptable leakage flow.
- NASA high temperature dynamic seal rig will provide unique capability to assess seal leakage change vs. wear cycles at temperature. Fabrication underway.

FUTURE PLANS

Over the next reporting period, several important tasks will be performed. The fabrication of the high temperature dynamic seal rig will be completed. The rig will be shipped to the site and made ready for test. Braided rope seals to be tested in the dynamic rig will be fabricated and prepared for test. And finally, NASA and Rocketdyne will cooperatively assess the tribological performance of candidate seal/panel materials for the metal heat-exchanger to back-up structure seals. These tests will be performed at temperature using NASA Lewis pin-on-disk tribometer.

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Future Plans (U)

- Complete fabrication/begin checkout of high temperature dynamic seal rig
- Complete fabrication of braided rope seal specimens for test in dynamic rig
- Cooperatively assess tribological performance of HEX to back-up structure seal materials with Rocketdyne

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Table I Linear Seal Hot Wear Screening
Seal Construction Matrix

Seal designation	Braid arch	Core					Sheath						
		Material	Denier	Fiber diam, μm	Number yarns	%	Material	Denier	Fiber diam, μm	Number carriers	Number layers	Number wires/yarns per tow	Braid angle
M1	2D	NX440	700	8	3166	94	IN600	569	100	24	1	5	80
M2	2D	NX440	700	8	3166	96	IN600	569	100	24	1	15	40
M3	2D	IN600	569	100	12,577	95	IN600	569	100	24	1	5	80
M4a	2D	NX440	700	8	3144	66	NX440	700	8	24	6	2	80
M4b	2D	NX312	600	8	3668	69	NX312	600	8	24	6	2	80
M5	3D	NX440	700	8	2647	70	NX440	700	8	36	(a)	(a)	40
M6	2D	NX550	2000	12	1076	87	NX550	2000	12	24	2	2	55

^aM5 THREE-DIMENSIONAL BRAID ARCHITECTURE:

- o Four interconnected braiding layers each layer consisting of 36 bundles (4 each 700 denier tows/bundle).
- o Axial (0°) stuffers: 90 axial bundles (4 each 700 denier tows/bundle) evenly distributed in four braiding layers.

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13. ABSTRACT (Maximum 200 words) Combined cycle ramjet/scramjet engines being designed for advanced hypersonic vehicles, including the National Aerospace Plane (NASP), require innovative high temperature dynamic seals to seal the sliding interfaces of the articulating engine panels. New seals are required that will operate hot (1200-2000 °F), seal pressures ranging from 0-100 psi, remain flexible to accommodate significant sidewall distortions, and resist abrasion over the engine's operational life. This report reviews the recent high temperature durability screening assessments of a new braided rope seal concept, braided of emerging high temperature materials, that shows promise of meeting many of the seal demands of hypersonic engines. The paper presents durability data for: (a) the fundamental seal building-blocks — a range of candidate ceramic fiber tows; and for (b) braided rope seal subelements scrubbed under engine simulated sliding, temperature and preload conditions. Seal material/architecture attributes and limitations are identified through the investigations performed. The paper summarizes the current seal technology development status and presents areas in which future work will be performed.					
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